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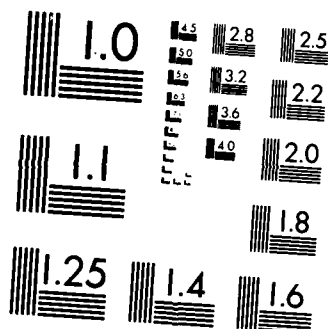   M B LONG ET AL. DEC 85 AFOSR-TR-86-0920 AFOSR-83-0205
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Final Report

to the

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July 1, 1983 - June 30, 1984

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A summary is given of the progress to date using two new laser/multichannel detection systems obtained with the DoD-University Research Instrumentation Program funding. Progress has been made in several different areas including: (1) high-speed mapping of gas concentrations in turbulent flows, (2) use of Rayleigh scattering for temperature mapping in turbulent diffusion flames, (3) measurement of the full three-dimensional scalar gradient in a plane, and (4) measurement of multipoint three-component velocities in a large volume. A summary of research in these areas is given along with a description of future studies to be carried out using the equipment acquired under this program.

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ABSTRACT

A summary is given of the progress to date using two new laser/multichannel detection systems obtained with DoD-University Research Instrumentation Program funding. Progress has been made in several different areas including: (1) high-speed mapping of gas concentrations in turbulent flows, (2) use of Rayleigh scattering for temperature mapping in turbulent diffusion flames, (3) measurement of the full three-dimensional scalar gradient in a plane, and (4) measurement of multipoint three-component velocities in a large volume. A summary of research in these areas is given along with a description of future studies to be carried out using the equipment acquired under this program.

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INTRODUCTION

Researchers associated with the Yale Center for Laser Diagnostics have been using laser scattering techniques to investigate a number of different physical processes. Although several different research areas are being actively pursued at the Center, a common base for these diverse experiments has been the use of laser scattering and multichannel detection systems which enable the simultaneous measurement of scattered intensities in the spatial and/or spectral domains. Through the efforts in this area, several new diagnostic techniques in the field of turbulence and combustion have been introduced. Under the DoD-University Research Instrumentation Program, we have sought to upgrade the facilities of the Center to keep pace with major advances in both detectors and lasers. The availability of these new systems has allowed the members of the Center to embark on totally new diagnostic programs in the turbulence/combustion field. These programs should provide new information on the mixing in turbulent reacting flows and on multipoint three-component velocities in a large volume. Obtaining such information would have been considered impossible prior to these advances in high technology.

RESEARCH ACCOMPLISHMENTS

During the initial period of the grant, a study was done to
determine the optimum source of the laser and detector systems that
were to be purchased. Since these are rapidly developing
technologies, the products available are in a constant state of flux.
After determination of the vendors, the equipment was ordered and
preliminary experiments were carried out with facilities existing
within the Center for Laser Diagnostics.

With the funds made available through this grant, the following
equipment was purchased:

1)   High-speed laser/imaging system including:

        High-speed two-dimensional diode array camera
            Microtex Corporation
            Model 7402
        Two-stage microchannel plate image intensifier
            ITT Electroptical Products Division
            Model F414420MCP
        Copper Vapor Laser System
            Plasma Kinetics, Inc.
            Model 451

2)   Three-dimensional velocity diagnostic system:

        1024 x 1280 Element High Resolution Camera
            Microtex Corporation
            Model 7602
        Nd:YAG Oscilator/Amplifier and Dye Laser
            Quanta-Ray, Inc.
            Models DCR-2A and PDL-1

Following is a summary of our work in the areas of research in which
the equipment has been used to date.

Temporal Development of Structures in Turbulent Flows

The importance of large-scale structures and the role they play in turbulence has prompted the development of several new experimental techniques for quantitatively measuring characteristics of these structures in two dimensions. Nozzle gas concentration distributions have been mapped out at a single instant by detecting the elastically scattered light from an aerosol laden flow.[1] In a similar way, other light scattering processes have been used for quantitative two-dimensional mapping of structures within turbulent flows, including Rayleigh scattering from gas molecules,[2] fluorescence,[3] and Raman scattering.[4] While the two-dimensional information offered by these techniques is valuable, the detectors used did not allow images to be recorded at a rate high enough to observe changes in the structures from one frame to the next. Thus it is difficult to study the evolution of large-scale structures utilizing these techniques.

High-speed imaging systems must be used to study the evolution of large-scale structures in a general way. The DoD-University Instrumentation program enabled investigators at the Center for Laser Diagnostics to obtain an electronically based system which is capable of high framing rates, directly quantifiable output, and real-time data display. This type of fast electro-optical data acquisition scheme holds great potential for applications in experimental fluid mechanics. By directly digitizing images consisting of a large number of points at a high repetition rate, one can extract such information

as convection velocities, the intermittency factor, or the mixing associated with a given structure as it travels downstream.

The experimental setup used for our initial high-speed imaging experiments is shown schematically in Fig. 1. The air was seeded with micron-sized aerosol particles and then passed through a 4 mm diameter axisymmetric nozzle. The nozzle was equipped with a stagnation chamber which was attached to a differential manometer for determining flow velocity.

An Ar^+ laser operated on all lines was pulsed using an acousto-optic modulator, then focused into a sheet and used to illuminate a radial cross section of the jet. The sheet of light was formed by passing the laser beam back and forth repeatedly between two opposing cylindrical reflectors as shown in the figure.

An image frame of $14.5 \times 14.5 \text{ mm}^2$ was imaged onto the photodiode array of a Reticon MC9128 camera, using two camera lenses. The Reticon camera was interfaced directly to an LSI 11/23 computer using a Microtex 7402 camera/computer interface with 1.25 Mbytes of high-speed memory. The pixel rate for this system was 8 MHz and, through software control, the user could designate the array width to be used, (i.e., number of pixels). When scanning the full 128 x 128 photodiode array, the detector could be operated at a framing rate of ∿400 Hz and a total of 80 frames could be collected in one data acquisition sequence. A much higher framing rate was necessary for the flow conditions considered here. To this end, the array was operated in a 128 x 32 pixel format which allowed for storage of 320 consecutive images. The data shown in Fig. 2 were collected at
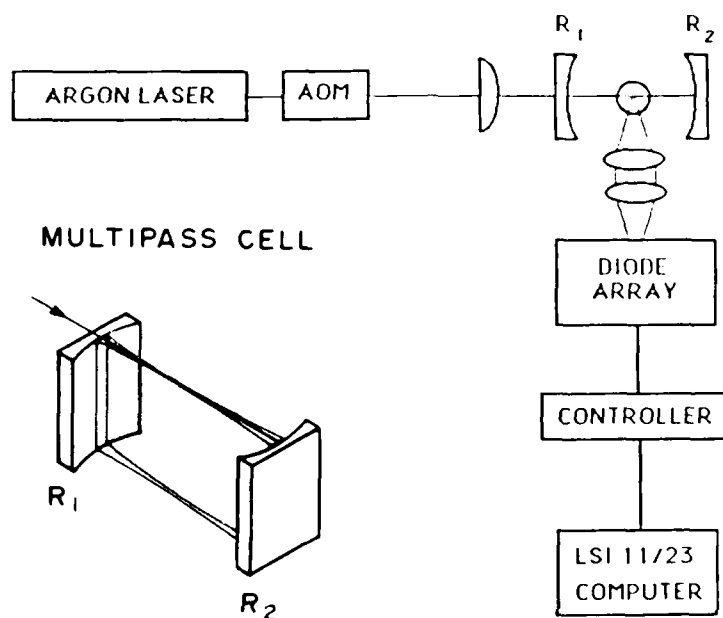
Fig. 1. Experimental configuration used for continuous
two-dimensional concentration measurements at 1.136 kHz.
The Ar$^+$ laser is pulsed using an acousto-optic modulator
(AOM) which is synchronized with a photodiode array.
The beam is formed into a thin sheet and the scattered
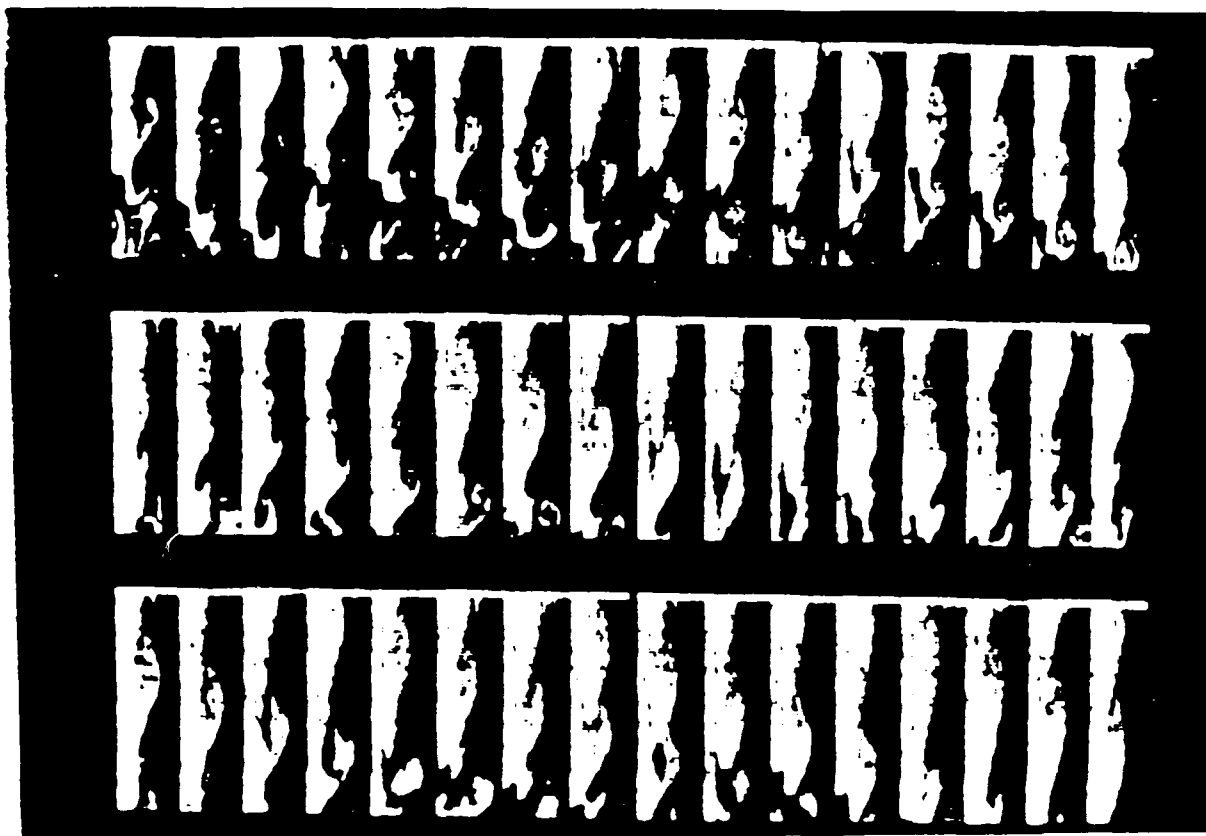light from the jet is proportional to the nozzle gas
concentration.

Fig. 2. A sequence of nozzle gas concentration measurements recorded at 1.136 kHz. The flow proceeds downstream from 4 diameters (top) to 7.5 diameters (bottom) at a rate of 3.4 m/sec.

1136 Hz. The flow velocity is 3.4 m/sec corresponding to a Reynolds number of 900. The region shown is from 4 to 7.6 nozzle diameters downstream. The pulse duration used here was 67 μsec with the laser operating at 5 W.

The raw data as collected by the camera have been corrected for background light and nonuniformities in the response of the camera and the illumination sheet. A dark background was recorded in the absence of the seeded jet. The response of the system was recorded by filling the entire image frame with a seeded gas that was passed through a large nozzle positioned directly into the sheet of light and then averaged over several realizations. The data were then divided by this image to correct for the nonuniformities in the camera, the illumination sheet, and the collection optics. These corrections ensure that the data obtained from these experiments are a quantitative measure of the gas concentration.

For the results described above, the diode array camera could be operated in an unintensified mode because of the relatively strong signals produced by Lorenz/Mie scattering from aerosols. In the future, an intensified version of the camera will be used in conjunction with the Cu vapor laser (Plasma Kinetics 451). With the intensifier and the high repetition rate available from the pulsed Cu vapor laser, the system will be able to detect molecular scattering mechanisms such as Rayleigh scattering and fluorescence at rates greater than 1 kHz.

Because a major fraction of the cost of such a low-light-level, high-speed camera system is the microchannel plate image intensifier

and the A/D conversion electronics, the solid-state detector was not permanantly attached to the intensifier. This will make it possible to take advantage of future advancements in solid-state detector technology (connected with VLSI development), as well as to change the resolution of the system by simply changing solid-state detectors.

Rayleigh Scattering Temperature Mapping

Our new, recently established capability uses Rayleigh scattering to provide an instantaneous mapping of the two-dimensional temperature distribution in a turbulent nonpremixed flame. In this work, the Rayleigh scattered light from an illuminated plane intersecting the flow field is imaged onto a computer-controlled low-light-level television camera and digitized in an 8,000 data point array. The fuel is a mixture of methane and hydrogen selected in proportions that will cause the Rayleigh cross section of the fuel gas mixture to be the same as that of the ambient coflowing air. For this fuel mixture, the Rayleigh scattered intensity will be directly proportional to the number density of molecules in the flow and, therefore, inversely proportional to the temperature.

Although Rayleigh temperature measurements have been previously reported for single-point measurements,[5] our work represents the first time that the technique has been applied in two dimensions. In this study, particular attention has been directed toward making the data obtained in this way as accurate as possible. This involves the proper correction of the data for both background level and nonuniformities of the illumination sheet and detector gain. These

data corrections are somewhat different from those required for
single-point Rayleigh measurements because of the special requirements
of two-dimensional imaging. The experimental details of the work and
calculated quantities based on the results have been accepted for
publication.[6]

Figure 3 shows a schematic representation of the experimental
configuration used for the two-dimensional mapping of temperature
using Rayleigh scattering. Three instantaneous temperature
measurements obtained with Rayleigh scattering from three different
laser shots are presented in Fig. 4. In the figure, the vertical
component of the plot represents the amplitude of the temperature at
each (x,y) coordinate in the flame.

This technique can be applied to a large number of diffusion and
premixed flames. The two-dimensional nature of these data makes
possible the study of large-scale structures in flows and, because the
data are quantitative, it is possible to calculate various statistical
quantities which can be expected to provide useful information on the
nature and role of large-scale structures in the flame.

Instantaneous Two-Dimensional Mapping of the Complete
Three-Dimensional Scalar Gradient

While the two-dimensional measuring techniques discussed above
represent significant progress in the effort to characterize
structures in turbulent flows, turbulence is known to be three
dimensional and even more information is needed to fully characterize
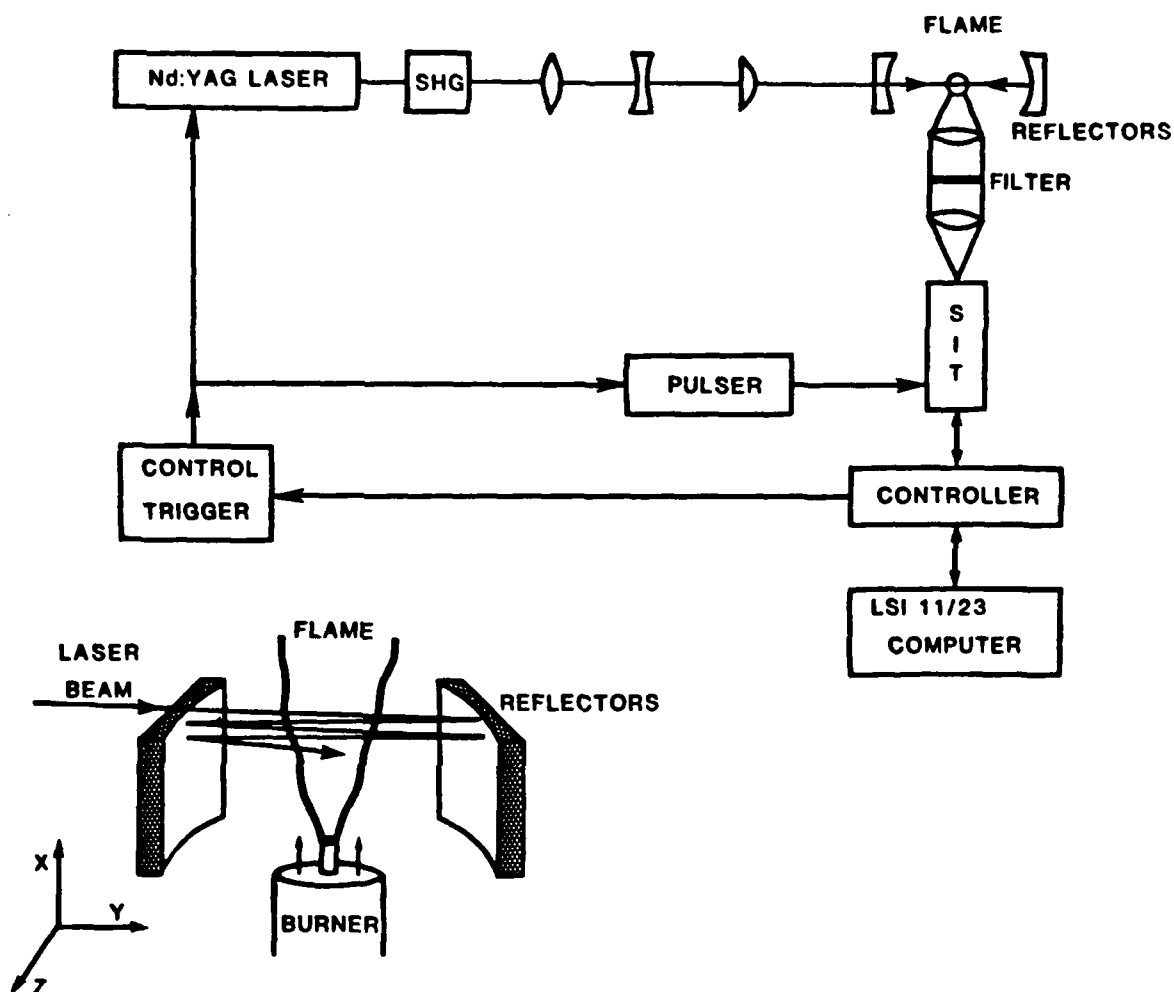the complex processes involved. For example, the joint probability

Fig. 3. Experimental apparatus used for obtaining the instantaneous
two-dimensional temperature measurement of a methane-hydrogen
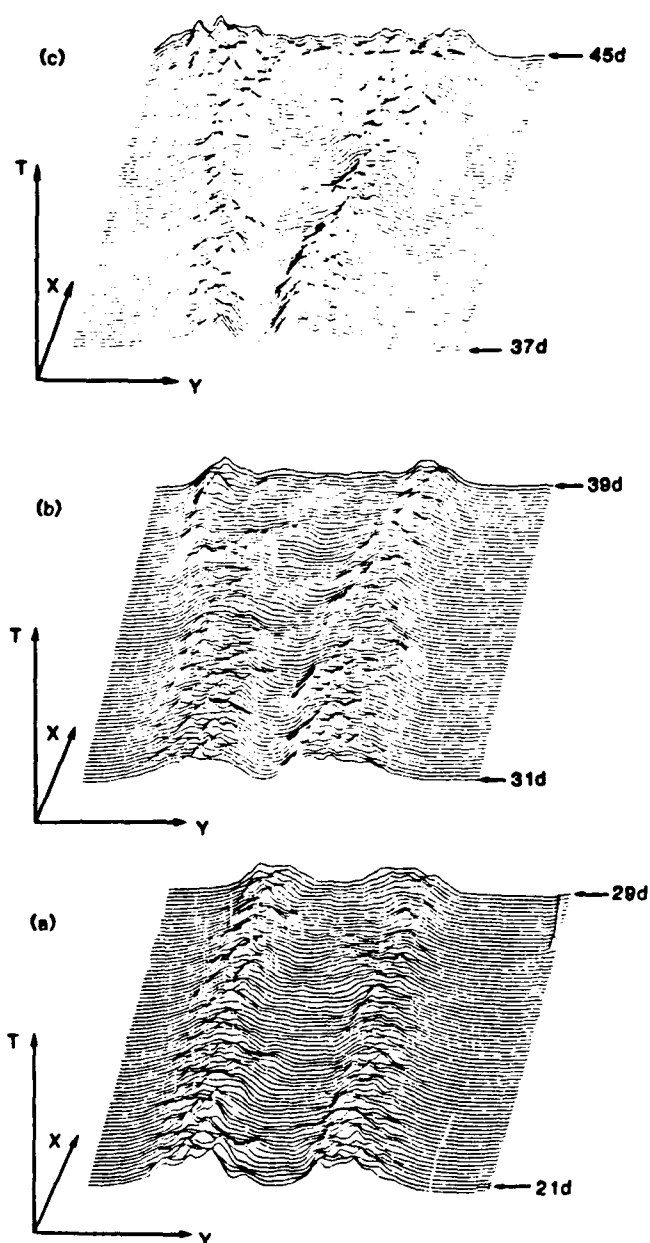diffusion flame.

Fig. 4. Instantaneous two-dimensional Rayleigh thermometry of a
methane-hydrogen diffusion flame (a) between 21 and 29 nozzle
diameters downstream, (b) between 31 and 39 nozzle diameters
downstream, and (c) between 37 and 45 nozzle diameters
downstream.

distribution function (pdf) of the gas concentration and the scalar

dissipation is of particular interest to modelers of combustion

because it is thought to give information about reaction rates in both

premixed[7] and diffusion[8] flames. To obtain this joint pdf,

instantaneous measurements of all three components of the

concentration gradient vector are needed.

Using the equipment purchased with this grant, a new technique

has been developed that allows calculation of all three instantaneous

components of the concentration gradient vector within a cross section

of a turbulent flow.[9] This is accomplished by the simultaneous

measurement of gas concentrations from two closely-spaced parallel

cross sections of the flow using laser Rayleigh scattering. The x and

y components of the gradient vector are calculated from data within

one of the cross sections and the z component is determined from

corresponding points in the two adjacent planes.

As depicted in Fig. 5, the vertically polarized second-harmonic

output of a pulsed Nd:YAG laser (Quanta Ray DCR-2A) was split into two

parts. Half the output was used to pump a dye laser (Quanta Ray PDL-1

using Rhodamine 6G), and the other half was apertured to produce an

energy comparable to the dye laser output. The resulting Nd:YAG

(532 nm) and dye beam (563 nm) energies were 4.7 and 8.8 mJ,

respectively. The two beams were then directed by independent

steering mirrors through the same sheet-forming optics. Adjustment of

the steering mirrors controlled the angle between the two sheets,

hence their separation at the nozzle. A linear photodiode array

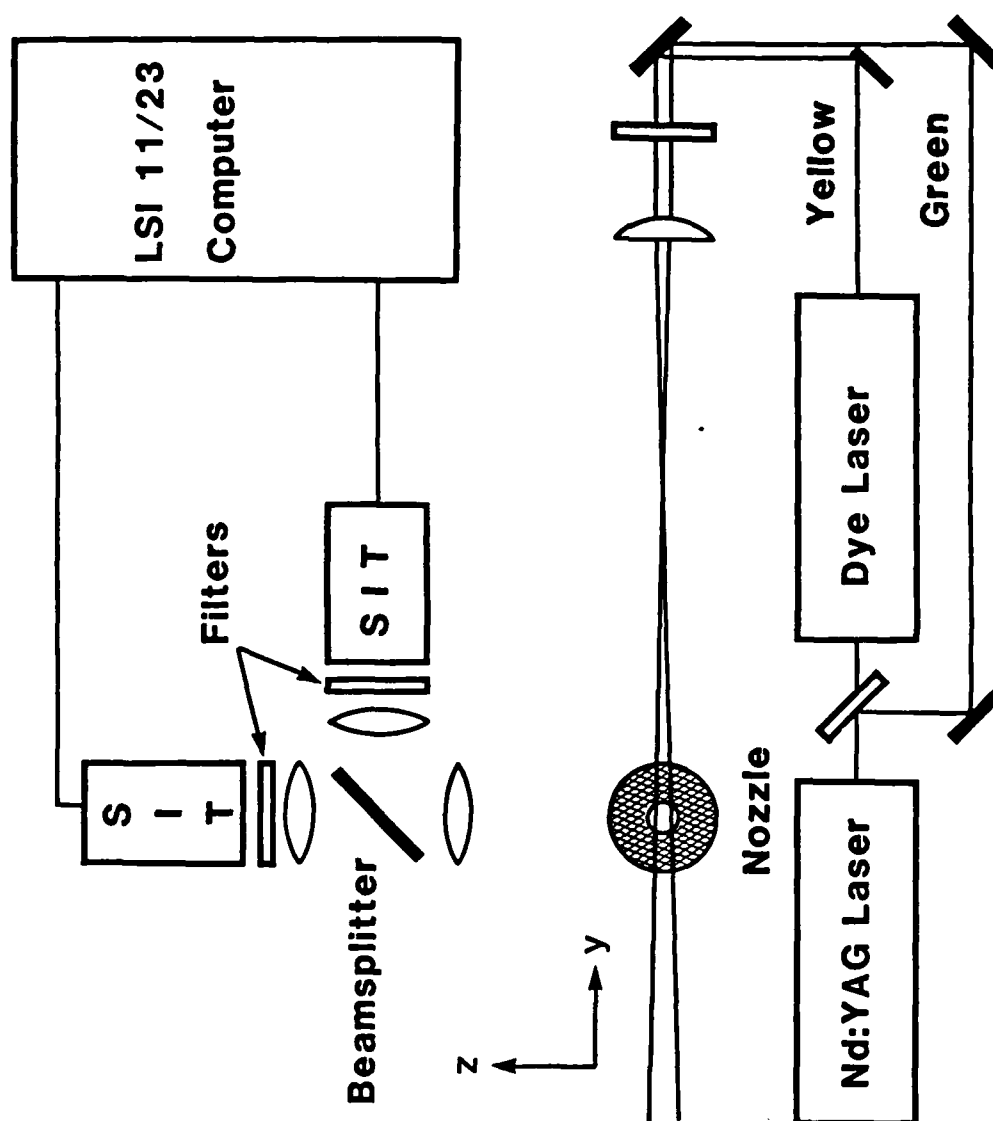(Reticon RL 512G) was used to measure the separation and widths of the

Figure 5

two sheets. The illumination sheets were parallel to the gas flow
ejected from the nozzle and intersected the flow at its center.

The Rayleigh scattered light from the two illuminated cross
sections of the jet was collimated by a single collecting lens. A
beam splitter then directed half the collected light to each of two
focusing lenses, which imaged the jet onto two silicon intensified
target (SIT) vidicon detectors (PARC OMA-2). These were controlled by
a single LSI 11/23 computer which coordinated the camera scanning and
data acquistion with the firing of the Nd:YAG laser. A different
optical interference filter positioned directly in front of each
camera ensured that each received light from only one of the two
sheets. The light collection configuration was chosen to minimize the
contribution of stray scattering from the surroundings to the raw
signal and was similar to that used in a previous two-camera
experiment.[10]

To demonstrate the capabilities of this technique, a jet of freon
ejected into air was investigated. The Rayleigh intensity
distributions from the flow field were digitized in a 65 x 78 pixel
format, corresponding to resolution volumes of 90 x 90 x 100 μm^3. The
maximum separation of the two sheets was 200 μm.

Statistical quantities of interest to combustion modelers can be
determined if a large number of instantaneous shots are taken. For
example, Fig. 6 shows the joint and independent pdf's of mixture
fraction and mixture fraction gradient from a point near the
centerline of the flow 14.9 nozzle diameters downstream. Similar data
for a point slightly further from the jet centerline are shown in
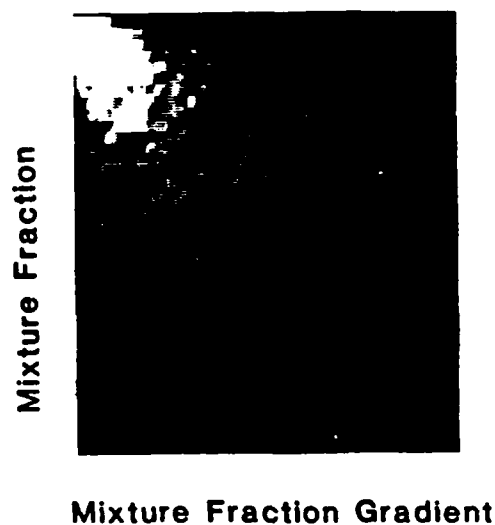
Mixture Fraction Gradient

(a) Joint probability density function (jpdf) of the mixture fraction and its gradient magnitude, calculated from 7000 instantaneous shots at a point 14.9 d downstream from the exit nozzle (diameter d = 3.5 mm) of a freon jet (Re = 3850), and at a radial distance of 0.13 d from the jet centerline. Lighter shading represents a higher joint probability.
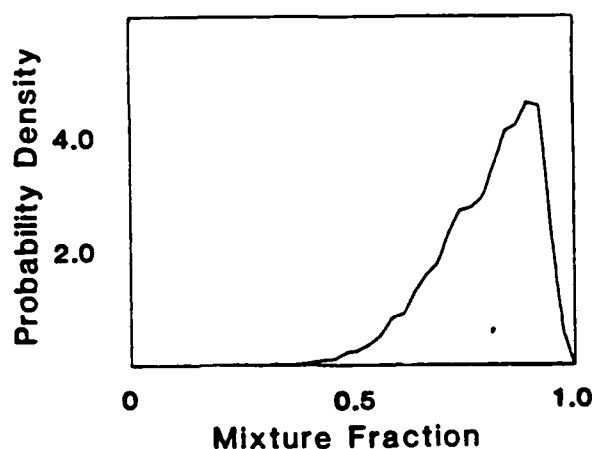
Mixture Fraction

(b) Independent pdf of the mixture fraction at the same location in the jet.

Mixture Fraction Gradient (mm^{-1})
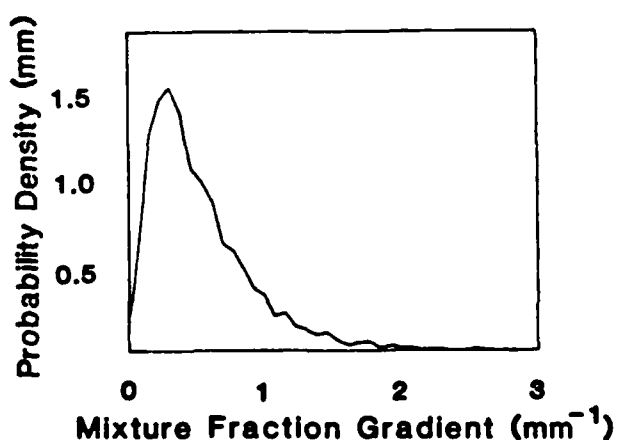
(c) Independent pdf of the mixture fraction gradient magnitude. The units of the pdf ensure that the area under the curve equals the dimensionless total probability of one.

Fig. 6.

Fig. 7. In both cases, the pdf's were obtained from 7000 shots.
Although the data shown here were obtained in a cold flow, the same
technique can be applied to flames.

Multipoint and Multicomponent Velocity Measurements
in Three-Dimensions

We are currently developing a holographic technique to use the
high resolution camera (Microtex 7602) and Nd:YAG laser (Quanta-Ray
DCR-2A) to measure the three-component velocity from many points
within the three-dimensional volume of the flow field. If a hologram
of an aerosol-seeded flow is taken at a time t, and again at a time
t + Δt later, the reconstructed double-exposure hologram can be used
to determine the velocity at locations in the flow where particles
were present. The Nd:YAG laser system will be used in a double-pulsed
mode to provide the high intensity required to produce the hologram
from the elastic scattering of the seeded particles within the flow.
By modulating the intensity of the two laser pulses, it will be
possible to unambiguously obtain the direction of the flow. In
addition, this will make it easier to determine which two images in
the hologram correspond to a single particle. Once the hologram is
developed, a means of digitizing the data contained in the
reconstructed image is required. The high resolution camera system is
needed to obtain the particle positions (and thus the velocity) with
sufficient accuracy.

We have successfully used the Nd:YAG laser system to make
sideband holograms of a thickly-seeded turbulent air jet. For these
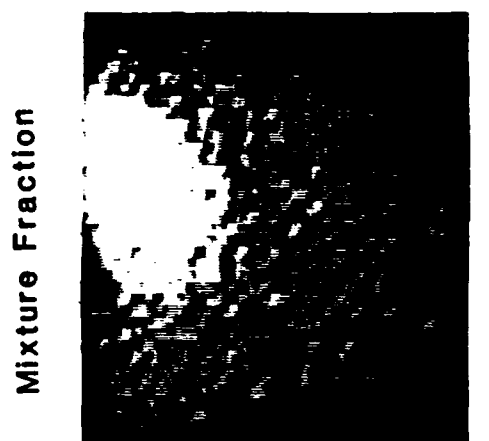
Mixture Fraction Gradient

(a) Joint probability density function (jpdf) of the mixture fraction and its gradient magnitude, calculated from 7000 instantaneous shots at a point 14.9 d downstream from the exit nozzle (diameter $d = 3.5$ mm) of a freon jet (Re $=$ 3850), and at a radial distance of 0.58 d from the jet centerline. Lighter shading represents a higher joint probability.
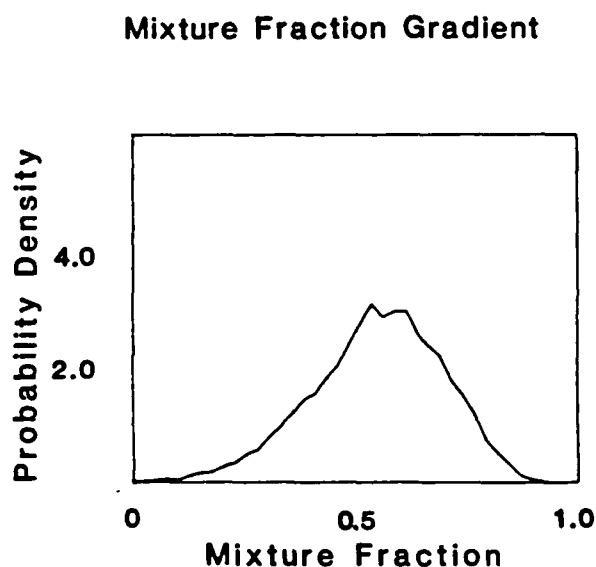
(b) Independent pdf of the mixture fraction at the same location in the jet.
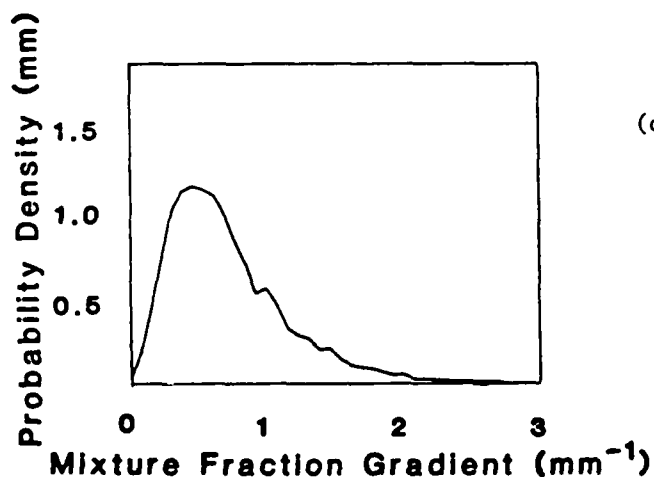
(c) Independent pdf of the mixture fraction gradient magnitude. The units of the pdf ensure that the area under the curve equals the dimensionless total probability of one.

Fig. 7.

experiments, the laser was operated with the electronic line narrowing accessory (Quanta-Ray ELN-2), which gave an experimentally determined average coherence length of approximately 15 cm. This is more than adequate for the three-dimensional velocity mapping technique under development. The average energy of 50 mJ per pulse was used to form a sideband hologram of aerosols entrained in a jet of air. Examination of the reconstructed image of the jet indicated that the hologram formed with this laser is capable of resolving micron sized particles.

The problems associated with the automated digital processing of the holographic images obtained are significant. In order to minimize these difficulties, much attention is being given to producing good quality, high resolution, and high contrast images of the aerosol-seeded flow. Concurrently, we are collaborating with experts in digital signal processing to determine the best techniques for use in obtaining velocities from the holograms.

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PERSONNEL

In addition to the three co-principal investigators, the
following graduate students have participated in the research
described above:

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Huey-Ming Tzeng

Michael Winter

Brandon Yip

Rena M. Zurn

END

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